N87-20932

SMALL-SCALE STRUCTURES AND THE DENSITY IRREGULARITY OF THE INNER CORONA

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ABSTRACT

We consider the observational evidence that the electron density irregularity factor $\langle N^2\rangle/\langle N\rangle^2$ is much greater than unity in the inner corona, in particular, evidence derived from the photometric comparison of K-corona emission pB with the EUV emission from coronal ions. We develop a simple mathematical model for the irregularity having a minimum number of parameters. We use this model to explore some implications of the observations and to show that well-known resolved structures such as polar plumes and coronal loops as presently understood cannot alone explain the irregularity.

INTRODUCTION

C. W. Allen (1963) introduced the term "coronal irregularity factor" defined as $x = \langle N^2\rangle/\langle N\rangle^2$ to describe the inhomogeneity of the solar corona. Here N (cm^{-3}) is the electron density. He compiled a table of estimates of x versus radial height based primarily on observed large scale structures such as streamers and condensations (Allen 1963, 1973). In this compilation x = 1.1 at R_o, 1.6 at 1.5 R_o, 2.5 at 2 R_o, increasing outward. Later, Allen (1975) substantially increased his estimate of x in the inner corona to $x \sim 4$ at 1 R_o increasing to ~30 at 1.5 R_o. These revised estimates were based on a statistical study of the daily λ284 FeXV intensity contour maps of the Sun obtained by the Goddard EUV spectroheliograph on the OSO-7 spacecraft. From a study of synoptic observations of the red and green forbidden lines and of the K-corona, Leroy and Trellis (1974) found the density irregularity to vary with the solar cycle. The coronal irregularity has been evoked in the interpretation of observed λ5303 polarization (Arnaud 1982) and of radio bursts (see Bougeret and Steinberg 1977).

In this paper we consider the observational constraints set on the coronal irregularity in the inner corona by direct cospatial and cotemporal photometric comparison of the intensity of EUV emission lines from coronal ions with K-coronal brightness pB (the polarization times the brightness). The local emission of coronal resonance emission lines depends primarily on the electron density squared, the chemical abundance, and the electron kinetic temperature, while the K-coronal emission due to Thompson scattering by free electrons depends directly on the electron density and on the local radiation field. Hence, combined EUV/K-coronal observations set a constraint on the irregularity that includes the contribution of both resolved and unresolved structures. We discuss photometric comparisons of the EUV and K-coronas and develop a simple model of coronal density irregularity based on structures embedded in the background corona. We use this as a basis for exploring the constraints set by observation on the irregularity and then consider whether the well-studied structures of the inner corona can account for it.

OBSERVATIONAL LIMITS ON THE IRREGULARITY

The first direct comparison of K-coronal brightness with the intensity of EUV emission lines was made by Withbroe (1970, 1971, 1972), who used EUV data from the Harvard spectrometer on the OSO-4 spacecraft and nearly cotemporal pB measurements made with the High Altitude Observatory's (HAO) Mark I K-Coronameter on Mauna Loa. Both sets of measurements were made at a fixed height of 2 arcmin (1.125 R_o) at all position angles around the limb. Withbroe found a strong correlation between pB and the EUV emission line intensities. He used the measurements of pB to put the EUV derived relative coronal abundances on an absolute scale relative to hydrogen and found them in reasonable agreement with the photospheric derived values. However, this derivation implicitly assumed that the coronal irregularity factor was unity.

More recently, a cotemporal and cospatial photometric comparison of the intensity of λ625 MgX and pB has been carried out based on radial scans of the inner corona between 1.05 and 1.25 R_o (Orrall, Rottman, Fisher, and Munro 1986a, b). The λ625 MgX intensities were obtained on rocket flights of the LASP EUV Coronal Spectrometer (Rottman, Orrall and Klimchuk 1982; Rottman 1986), and the pB measurements were made with the HAO Mark III K-Coronameter on Mauna Loa (Fisher, Lee, MacQueen and Poland 1981).

These new measurements show the same high correlation between λ625 intensity and pB found by Withbroe (1972). The λ625 intensities measured with the LASP EUV Spectrometer are in good average agreement with the Harvard measurements on OSO-4, OSO-6 and Skylab. However, a recent intercomparison of the HAO K-coronameters and eclipse cameras shows that the pB values provided by the Mark I K-coronameter (including those used by Withbroe) are too bright by about a factor of 4 (Fisher and Sime 1984; Fisher and Munro 1986). When the pB values used by Withbroe are corrected by this factor, they are in essential agreement with our more recent study.

Let E (ergs cm^{-3} s^{-1} sr^{-1}) be the local coronal emission of λ625 MgX. With the assumptions of gravitational hydrostatic equilibrium and large-scale spherical symmetry, the λ625 and pB measurements can be inverted to recover $\langle E\rangle$ and $\langle N\rangle$, respectively, as functions of height in the inner corona. Here we express E and N as average values, since the inner corona is to some unknown extent nonuniform or structured on scales short compared to the length of the observing column. For convenience we write the well-known and commonly used expression for the emission of a collisionally excited coronal resonance line (see Dere and Mason 1981) as $E = AN^2H(T)$. Here A is the coronal abundance of Mg relative to hydrogen. For Mg the coronal abundance is thought to be close to the photospheric value, $A \sim 4 \times 10^{-5}$ (see Meyer 1985). H(T) contains all of the constant and temperature dependent terms. For λ625 MgX it has a maximum between $T = 10^{6.0}$ and $10^{6.1}$ K (see Figure 1). We can then find from $\langle E\rangle$ and $\langle N\rangle$ derived from observation the quantity $\langle E\rangle/\langle N\rangle^2 = \langle AH(T)N^2\rangle/\langle N\rangle^2$, assuming the photospheric abundance for Mg and using the upper limit to H(T) yields a lower limit to the irregularity $x = \langle N^2\rangle/\langle N\rangle^2$.

In a coronal hole near the south pole observed on 1983 July 25 this lower limit to x was found to be ~10 (Orrall et al. 1986a). Since the temperature implied by the observed scale height was $\sim 10^{6.0}$ K, the actual value of x was evidently close to this lower limit. Above an active region observed on 1980 July 15 the lower limit to x was found to be ~6, but since the observed scale height implied $T \sim 10^{6.3}$ K, the actual value of x implied is ~30 (see Fig. 1). (The pB and EUV scale heights yielded the same temperature. This was also true in the coronal hole.) Similar large values of x are implied by Withbroe's data after correction as described above. Since Withbroe's data samples all position angles around the limb, this suggests that the inner corona has this large irregularity at all latitudes.

A MODEL FOR THE IRREGULARITY

Consider a two-component density model of the inner corona in which there are structures with electron density N_S filling a fraction α of the coronal volume. These are embedded in a background or ambient corona of density N_C. Then $\langle N \rangle = N_S\alpha + N_C(1 - \alpha)$ and $\langle N^2 \rangle = N_S{}^2\alpha + N^2(1 - \alpha)$. If we define $\beta = N_S/N_C$, then the coronal irregularity factor is given by $x(\beta;\alpha) = [\beta^2\alpha + (1 - \alpha)][\beta\alpha + (1 - \alpha)]^{-2}$. For a given value of β, $x(\beta,\alpha)$ has a maximum $x_{max} = (\beta + 1)^2/4\beta$, which occurs at $\alpha = \alpha^*$, where $\alpha^* = (\beta + 1)^{-1}$. Thus, a given value of x implies a lower limit to β such that $\beta \geq (2x - 1) + [(2x - 1)^2 - 1]^{1/2}$, or if $x \gg 1$, then $\beta \geq 4x$. Since x approaches α^{-1} for large β, then $\alpha < x^{-1}$ (see Fig. 2).

The actual values of N_C and N_S are related to the observed mean density $\langle N \rangle$ by $N_C/\langle N \rangle = [\beta + (1 - \alpha)]^{-1}$ and $N_S/\langle N \rangle = \beta[\beta\alpha + (1 - \alpha)]^{-1}$, respectively. For the special case where β has the minimum value for a given value of x (that is where $\alpha = \alpha^*$) these ratios become $N_C/\langle N \rangle = (1 + \beta)/2\beta$ or ~1/2 for $\beta \gg 1$, and $N_S/\langle N \rangle = \beta(1 + \beta)/2\beta$ or $\sim\beta/2$ for $\beta \gg 1$. Thus even when β is large, the ambient density N_C need not be less than 1/2 the mean observed value.

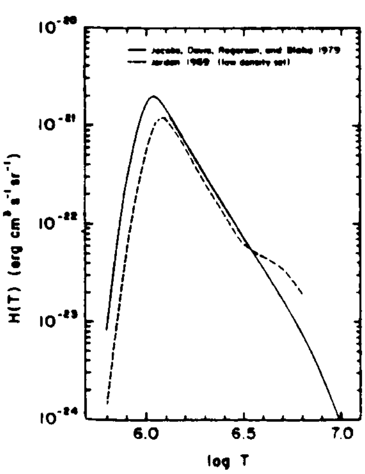

Figure 1. The function H(T) for λ625 MgX

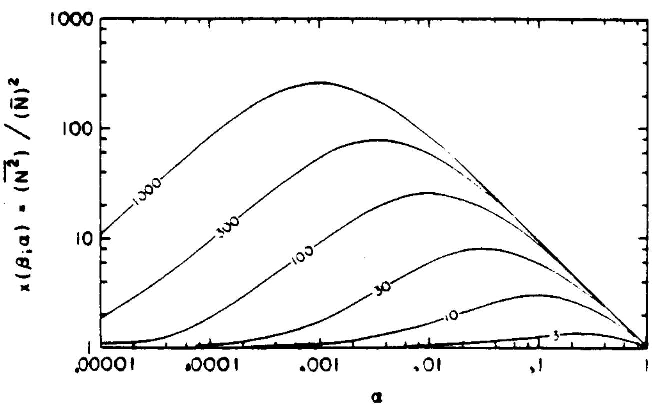

Figure 2. The coronal irregularity factor $x(\beta;\alpha)$ for several values of β.

CONTRIBUTIONS OF KNOWN CORONAL STRUCTURES

Using this model, we consider whether well-known coronal structures can account for the observed irregularity. The value of $x \sim 10$ inferred in the coronal hole observed in 1983 implies $\beta > 40$ and $\alpha < 0.1$. The minimum value $\beta = 40$ occurs at $\alpha^* = 0.024$. The best known structures in the inner polar corona are polar plumes (or rays) studied on white-light eclipse images. Saito (1965) found the average ratio of electron density in the plumes to that in the ambient corona (i.e., the quantity we have called β) to increase from 3 to 5 between 1.1 and 1.5 R_o, respectively, and he compares this with previous published values ranging from 3 to 9. The temperature implied by the observed scale height was found to be 1.2×10^6 K and 1.0×10^6 K in the plumes and in the ambient corona, respectively.

Ahmad and Withbroe (1977) analyzed three well-defined plumes on λ625 MgX and λ1032 OVI images from the HCO/Skylab experiment. They found the plume density to be about three times greater than typical coronal hole models and $T \sim 1.1 \times 10^6$ K. Although plumes are too cool to be easily seen in soft X-rays, Ahmad and Webb (1978) studied plumes with bright points at their base on images from the S-054/Skylab experiment. Their pressure measurements in the plumes imply a density of about 10^8 cm^{-3} at 1.1 R_o, roughly a factor of 2 less than that found by Saito (1965). Newkirk and Harvey (1968) studied plumes from white light eclipse observations made at three eclipses near sunspot minimum. They also found a core density in the plumes of about 10^8 cm^{-3}. They chose not to express plume densities in terms of the background density because of the observational difficulty in establishing the true density of the polar background corona (see Ney et al. 1961).

Thus most studies of plumes find values of β between 3 and 7 in the low corona. Unless these studies are incorrect (e.g., because of the difficulties of inferring the true density of the background polar corona as discussed by Newkirk and Harvey 1968), polar plumes cannot explain an irregularity as large as $x \sim 10$ in the polar corona.

The value of $x \sim 30$ inferred in the active region in 1980 July (near the edge of a nonflaring region) implies $\beta > 120$ and $\alpha < 0.033$. The minimum value $\beta = 120$ occurs at $\alpha^* = 0.0083$. Coronal loops are the most obvious and most studied structures that might produce this irregularity. The scaling law for quasistatic loops of Rosner et al. (1978), namely $T_m = 1.4 \times 10^3(pL)^{1/3}$ can be used to estimate the density. We take for the maximum temperature $T_m = 2 \times 10^6$ K, and for the total length L of the loops, 0.3 R_o. The resulting pressure p then implies an electron density $\sim 2.5 \times 10^8$ cm^{-3}. This is about the density of polar plumes at this same height (see Saito 1965) and only slightly greater than the mean coronal density at this height. This suggests that quasistatic coronal loops do not produce the observed irregularity at these heights in the inner corona.

SUMMARY AND DISCUSSION

The coronal density irregularity inferred from comparison of the EUV and K-coronas is large at all latitudes and cannot easily be explained by the most obvious resolved structures of the inner corona as they are presently understood. One possibility is that it results from the small resolved and incipiently resolved structures visible on high resolution coronal images in white light (see Newkirk 1967) and in the EUV (Brueckner and Bartoe 1974). On the other hand, it might arise in much smaller structures, possibly in instabilities or in density fluctuations associated with coronal heating.

Finally, it is necessary to point out that the value of the irregularity inferred from an EUV/pB comparison is sensitive to systematic errors in the absolute photometry--especially to errors in pB since it enters as the square into the determination of x. Additional observations are obviously needed. The density irregularity is clearly an important and basic physical parameter of coronal physics that can be quite directly estimated from observation.

We wish to thank Dr. A. N. McClymont for valuable discussion. This research was supported by NASA in part under grants NSG-5178 and NGL 12-001-011 and by a travel grant to one of us (FQO) to attend the Coronal and Prominence Plasmas Workshop.

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